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CHAPTER 6

ELECTRICAL PROPERTIES OF INSULATING MATERIALS

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1. INTRODUCTION

Electrical properties of interest for insulation materials can be classified into two major categories:

- Those of significance at low voltage operating stresses
- Those of importance at high voltage operating stresses

At low stresses, the properties of interest relate to dielectric constant, power factor, and conductivity (resistivity). Dielectric constant represents the ability of the insulation to "hold charge." Power factor represents a measure of the amount of energy lost as heat rather than transmitted as electrical energy. A good dielectric (insulation) material is one that holds little charge (low dielectric constant) and has very low losses (low power factor). Polyolefins represent examples of polymers that possess excellent combinations of these properties. This is discussed in depth in Chapter 5.

At high stresses -- greater than operating stress -- the characteristic of importance is dielectric strength. Here, the insulation must be resistant to partial discharges (decomposition of air in voids or microvoids within the insulation). Also of interest is the inherent ability of the polymeric insulation material to resist decomposition under voltage stress. Unfortunately, the measured dielectric strength is not a constant, but has a variable value depending upon how the measurement is performed. This will be discussed later in this chapter. In any event, the dielectric strength must be "high" for the insulation to be functional. This chapter will review factors that influence electrical properties at low and high voltage stresses.

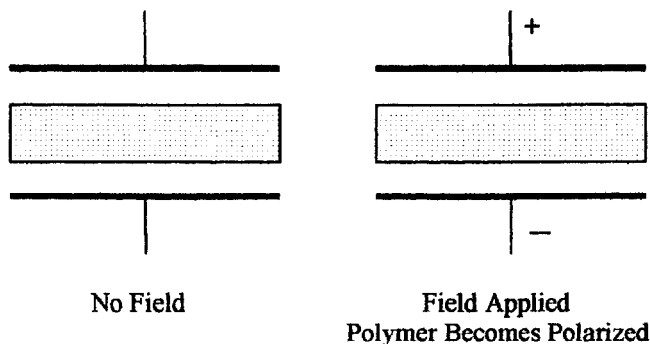
2. STRUCTURE-PROPERTY RELATIONSHIPS

The electrical properties of an insulation materials are controlled by their chemical structure. Chapter 5 reviewed the inherent chemical structure of polyolefins, and described how the structure influences physico-chemical properties. In this chapter, we shall review how these factors influence the electrical properties. The emphasis shall be on polyolefins.

Low stress electrical properties are determined by the polar nature of the polymer chains and their degree of polarity. Polyethylene, composed of carbon and hydrogen or methylene chains, is non-polar in nature, and has low conductivity. If a polar component, such as a carbonyl, is on the chain, the polymer chain now becomes more polar and the characteristics that lead to low conductivity are diminished. Ethylene copolymers with propylene retain their non-polar nature since the propylene moiety is as non-polar as is the ethylene moiety.

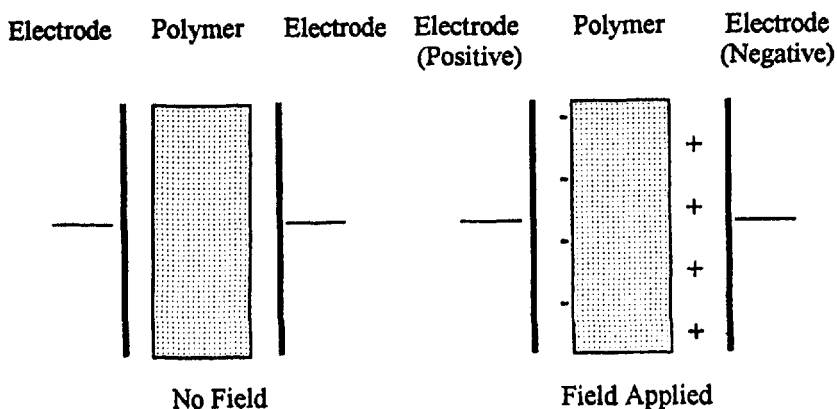
When a polyolefin is subjected to an electrical field, the polymer chains have a tendency to become polarized. Figure 6-1 shows what happens when a polymer is "stressed" between electrodes, with different polarities resulting. Figure 6-2 shows how the polymer insulation material responds. There is a tendency for the positive charges on the polymer to move toward the negative electrode, and for the negative charges on the polymer to move toward the positive electrode, hence pulling the polymer in two directions. This is a general description, and does not take into account the chemical structure, which is discussed later.

Figure 6-1
Polarization of a Polymer Subjected to an Electric Field



Schematic description of a polymer subjected to electric field; polymer becomes polarized.

Figure 6-2
Charge Migration on Polymer Chains Subjected to Electric Field



Insulation response to electric field application. Positive charges on polymer chain migrate toward the cathode and negative charges migrate toward the anode.

Where do these charges come from? After all, we have described the polyolefins as being comprised of carbon and hydrogen, and as not being polar compared to say the polyamides or ethylene copolymers possessing carbonyl or carboxylate groups. It can be noted that such description is “ideal” in nature. While being technically correct for a pure polyolefin, in the real world there are always small amounts of such polar materials present. This will be discussed later.

Figure 6-3 shows what may happen to a polymer insulation material that has polar groups on the side branches, rather than on the main polymer chain. Note that in this idealized description of the “folded” chain, the main chain does not undergo any movement under voltage stress. The side chains, which were once “random,” are now aligned toward the electrodes. Figure 6-4 shows a “more realistic” coiled polymer chain with polar branches. Note how the alignment toward the positive and negative electrodes has taken place.

Figure 6-3

Schematic Description of Orientation of Polar Functionality on Polymer Side Chains Subjected to Electric Field



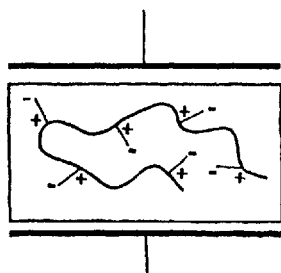
No Voltage

Voltage Stress Applied

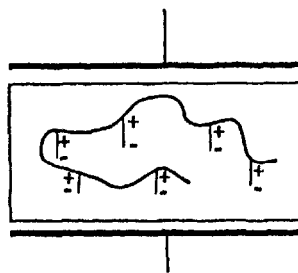
Under voltage stress, a polar chain orients toward the cathode or anode, depending upon the charge it possesses. The non-polar chain does not migrate.

Figure 6-4

Polarization of Side Chains Depicted on a Coiled Polymer



No Voltage Field

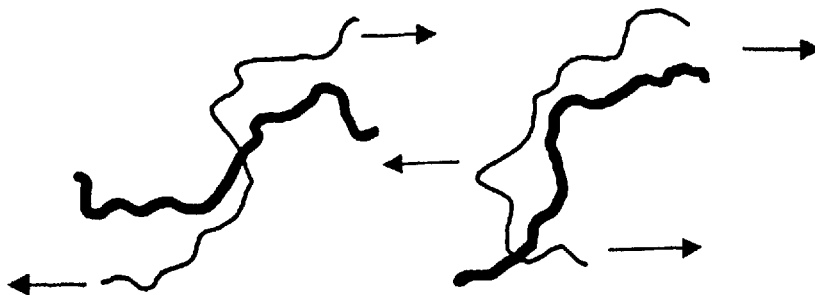


Field Applied
Polymer Becomes Polarized

A polymer is typically coiled, as shown here. The positive charges on a polymer are attracted to the cathode. The negative charges are attracted toward the anode. The movement of these charged regions causes motion of the entire side chain.

In Figure 6-5, we show what happens to the main chain. Prior to this, we had considered what happened to the relatively short branches. However, the entire main chain may undergo motion also, assuming it possesses functional groups that respond to the voltage stress. The figure shows that entire chain segments may move and rotate, in accordance with the field.

Figure 6-5
Main Chain Motion of Polymer Subjected to Electric Field



When the main chain length possesses charged regions, the entire main chain may exhibit motion under the electric field. Here, the center portion of the thin chain migrates to the left. The lower portion of the chain, depicted here as being thick, migrates toward the right. The depiction indicates that one chain is positively charged and the other is negatively charged.

It should be emphasized that this description is what would happen under dc. Consider now what would happen under ac; here the alignments will have to be shifting back and forth in accordance with the polarity change. Furthermore, this will take place at a rate controlled by the frequency. In considering these points, it becomes evident that the response of a polyolefin polymer, even a slightly polar one, is quite different under ac than dc. The next question to consider is what happens if the movement of the chains cannot “keep up” with the change in frequency? Of course, our interest is in the 50 to 60 hertz range, but to understand the polymer response, it is desirable to review what happens over a very broad frequency range. This is reviewed in the Section 3.0. Before entering that subject, it is necessary to recall that the polymer chains that we have been considering consist of many, many methylene groups linked together and these are non-polar in nature. However, after formation (polymerization), these very long chains are always subjected to small chemical changes. These small chemical changes, known as oxidation, may occur during conversion of the monomer to the polymer. This may also occur during conversion of the polymer to a fabricated part (in our case, the cable insulation). When extrusion is performed, the polymer is heated to very high temperatures in an extruder barrel, and is subjected to mixing and grinding due to screw motions. As noted earlier, an effort is made to prevent this elevated-temperature-induced degradation (but more realistically, the effect is kept to a minimum) by incorporating an antioxidant into the polymer. The antioxidant preferentially degrades and protects the polymer insulation. However a small degree of oxidative degradation cannot be prevented, and always occurs. Therefore there will always

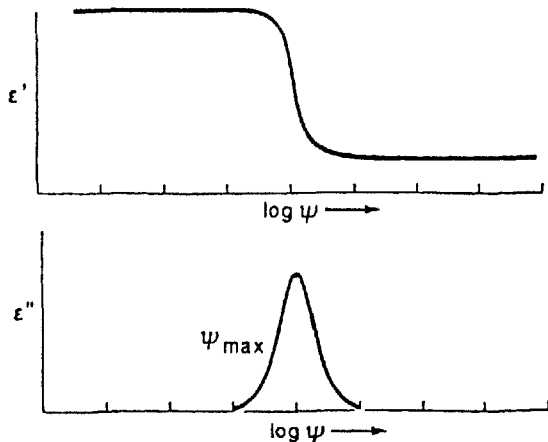
be some oxidized functional groups on the polymer chains. These are important points to keep in mind when reviewing the polymer insulation response to frequency.

3.0 DIELECTRIC CONSTANT AND POWER FACTOR

Different regions of the polymer chains will be sensitive and respond differently to voltage stress. This phenomena is intimately related to the frequency. Different functional groups will be sensitive to different frequencies. When the "proper" frequency-functional group combination occurs, the chain portion will respond by moving, e.g., rotating. Since this phenomenon is frequency dependent, one might expect that different responses will result from different functional group-frequency combinations. This is exactly what occurs. Referring to the top curve in Figure 6-6, we can see that at low frequencies, when stress is applied, the polar region-dipoles-can respond and "accept" the charge, and align as described above. The dielectric constant is relatively high under these conditions. As the frequency increases, no change occurs in this effect will occur as long as the dipoles can respond. At some point as the frequency continues to increase, the chains will have difficulty responding as fast as the field is changing. When the frequency change is occurring at so rapid a rate that no rotation can occur, the charge cannot be held and the dielectric constant will be lowered.

Figure 6-6

Dielectric Constant and Power Factor as a Function of Frequency



Upper portion of Figure 6-6 depicts the change in dielectric constant with frequency. The lower portion of the figure depicts the change in power factor with frequency.

For a polymer like polyethylene, with very small amounts of polar functionality, the dielectric constant is always low (compared to a more polar polymer such as a polyamide [Nylon for example]). However, oxidized regions will respond more readily due to their more polar nature. The reason for the change in dielectric constant with frequency is clear. It should also be noted that other parameters affect this property; e.g., temperature. In essence, any change that affects motion of the polymer chain will affect the dielectric constant.

The point where the polymer chain segments undergo change in rate of rotation is of special interest. The lower curve of Figure 6-6, focusing on losses (e.g., power factor), shows a peak at this point. In considering power factor, the same explanation applies; changes are affected by frequency and specific polymer nature. At low frequencies, the dipoles on the polymer chains follow variations in the ac field, and the current and voltage are out of phase; hence the losses are low. At very high frequencies as noted above, the dipoles cannot move rapidly enough to respond, and hence the losses are low here also. But where the change is taking place, the losses are greatest. This can be visualized by thinking in terms of motion causing the energy to be mechanical rather than electrical in nature. It is common to refer to the dielectric constant and power factor at 50 or 60 Hertz, and at 1,000 hertz.

In relating the information shown in Figure 6-6 to the earlier figures, it is to be noted that the polar functionality can be due to motion of main chains or branches. Where the oxidized groups are the same, as in carbonyl, one could expect that the chains (ideally) to respond the same way at the same frequency. But what happens if there are different functional groups present such as a carbonyl, carboxyl, or even amide or imide functionality? Also, how does the main chain nature affect all this? The answer is that these factors are quite significant. Different functional groups will respond differently at the same frequency, and the main chain can hinder motion due to its visco-elastic nature. If the dipole is rigidly attached on the polymer backbone, then main chain motion is going to be involved. If the dipole is on a branch, it can be considered to be flexibly attached, and the rate of motion of the branch will be expected to differ from the main chain, even if the functional group is the same. The end result of all of this is a phenomenon called dispersion. Here the chains move at different rates at any single frequency and temperature. They may exhibit a change over a broad region rather than a sharp, localized region as the frequency and temperature is changed slightly.

For purposes of understanding power cable insulation response, the main interest is, of course, at 50 or 60 hertz. Also, our interest is in what is intended to be relatively non-polar systems. It is necessary to remember that no system is perfect and there will be variations in degrees of polarity not only from one insulation material to another, and not only from one grade of the same material

to another, but perhaps also form one batch of supposedly identical material to another. Much depends upon the processing control parameters during extrusion.

The literature reports dielectric losses of many different types of polyolefins as a function of temperature, at controlled frequencies. Hence, it is known that conventional low density polyethylene undergoes losses at various different temperatures. In addition, antioxidants, and antioxidant degradation by products, low molecular weight molecules, will also respond, and this complicates interpretation. With conventional crosslinked polyethylene, the situation is even more complex as there are peroxide residues and crosslinking agent by-products. These low molecular weight organic molecules, acetophenone, dimethyl benzyl alcohol, alpha methyl styrene, and smaller quantities of other compounds, will gradually migrate out of the insulation over time. Hence interpretation of data requires not only knowledge of the system, but some degree of caution is prudent. In addition to all of this, if there are foreign contaminants present, it is possible that they also can influence the measured dielectric constant and power factor.

The dielectric constant of polyethylene is dependent upon the temperature and frequency of testing. At constant temperature, it is reduced slightly as the frequency increases; at constant frequency, it increases with temperature.

4. DIELECTRIC STRENGTH

The dielectric strength of an insulation material can be defined as the limiting voltage stress beyond which the dielectric can no longer maintain its integrity. The applied stress causes the insulation to fail; a discharge occurs which causes the insulation to rupture. Once that happens, it can no longer serve its intended role. Unfortunately, the dielectric strength is not an absolute number; the value obtained when dielectric strength is measured depends on many factors, not the least of which is how the test is performed. Therefore, it is necessary to review the issues involved, so that the value and the limitations of the term "dielectric strength" are well understood.

The dielectric strength is usually expressed in stress per unit thickness--volts per mil, or kV per mm. For full size cable, it is common to merely report the kV at which the cable has failed. Hence if a 175 mil wall cable fails at 52.5 kV (or 52,500 volts), the dielectric strength can also be expressed as 300 V/mil.

The most obvious value of dielectric strength is called the intrinsic strength. This is defined by the characteristics of the material itself in its pure and defect-free state, measured under test conditions that produce breakdown at the highest possible voltage stress. In practice, this is never achieved experimentally. One

reason, as noted above, is the difficulty in attaining a defect-free pure insulation specimen. The closest one can come is on measurement of very thin, carefully prepared films with appropriate electrodes. (The thinner the film, the less the chance for a defect to exist.) Under these ideal conditions, the insulation itself would fail due to its inherent properties (bond strength rupture).

It is more likely is that failure will occur under discharge conditions; here, gas (e.g., air) present in small voids in the insulation, present due to processing characteristics, will undergo decomposition. Air is the most likely gas present for polyethylene and crosslinked polyethylene (in contrast to vapors of crosslinking by products). Its intrinsic dielectric strength is significantly less than that of polyethylene. Under these conditions, the discharges that take place in these small void(s) leads to "erosion" of the insulation surface in contact with the air. This in turn leads to gradual decomposition of the insulation and eventual failure. The decomposition of the air in the voids occurs at voltage stresses much lower than the inherent strength of the polyethylene itself. For example, the dielectric strength of a one mil thick film of polyethylene measured under identical conditions to a layer of air (atmospheric pressure), gives a dielectric strength value 200 times greater. Polyethylene give value of about 16,500 volts per mil, while that of air is about 79. The dielectric strength of air increases with pressure (that of polyethylene does not change), and this concept has commercial impact; however the degree of improvement is small. By increasing the pressure by a factor of 6, the dielectric strength increases by a factor of about 5 -- still well below that of the polymer film.

When focusing on extruded cable insulation, we are now concerned with relatively thick sections; 175 to 425 mil walls for distribution cables, and even thicker walls for transmission cables. Discharges that occur in these practical systems may not lead to immediate failure. It is possible that the discharge will cause rupture of a portion of the wall, and then cease. This could be related to the energy of the discharge, the size of the adjacent void, and, of course, the nature of the insulation material. When this occurs, we will develop a blackened needle-shaped series of defects, sometimes resembling a tree limb; these are called electrical trees. Discharges may occur repetitively, and hence the tree will appear to grow. In time the "tree" will bridge the entire insulation wall and cause failure. Discharges may also occur on the surface of the insulation, particularly if there is poor adhesion between the insulation and shield layers.

Another mechanism of failure is known as thermal breakdown. This occurs when the insulation temperature starts to increase as a result of aging phenomena under operating stress. Under voltage stress, some insulation systems will start to generate heat, due to losses. If the rate of heating exceeds the rate of cooling (that normally occurs by thermal transfer) then thermal runaway occurs, and the insulation fails by essentially, thermally induced

degradation. Several points should be kept in mind here:

- (1) The heat transfer capability of polyolefins is low, and heat dissipation is not normally rapid
- (2) These events may occur in the presence or absence of discharges
- (3) The presence of inorganic fillers contributes to increasing the dielectric losses, and may exacerbate the situation. Also, some organic additives in the insulation may also lead to increasing the dielectric losses/ Finally, it should be noted that thermal breakdown of polyolefins is a very well-studied area.

Although not a direct cause of failure, mention should be made of water treeing; water trees lead to a reduction in dielectric strength, but are not a direct cause of failure. These trees have a different shape for electrical trees, and also have different cause. The differences are outlined below.

WATER TREES

Water required
Fan or bush shaped
Grow for years
Microvoids connected by tracks

ELECTRICAL TREES

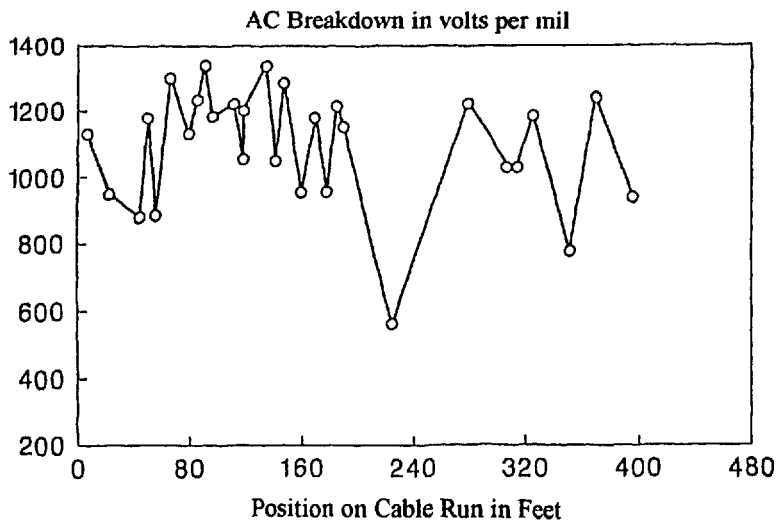
Water not required
Needle or spindle shaped
Failure shortly after formation
Carbonized regions

Water trees grow under low (normal) operating stress, do not require the presence of "small voids," and lead to a reduction in dielectric strength. Laboratory studies have shown that such trees can penetrate virtually the entire insulation wall yet not lead immediately to failure. As the chart shows, the "channels" or "tracks" that comprise water and electrical trees differ.

AC breakdown strength is commonly performed on full size cables as an aid in characterization. For full size cables, it is common to perform many such tests of long lengths of cables (e.g., 25 to 30 feet) and plot the data on Weibull or Log normal curves. This is done as the data always has some variation. A good example is data developed on a project for the Electric Power Research Institute (EPRI).

Figure 6-7

AC Breakdown Strength of 15 kV XLPE Insulated Cable as a Function of Position on Reel that Contained 5,000 Feet of Cable and Total Extrusion Run was 50,000 Feet



In Figure 6-7, it is seen that the dielectric strength of full size cables varies from a low of about 600 V/mil to a maximum of about 1,300 V/mil. This demonstrates that although the cable was manufactured in presumably the same manner (this cable was tested from the same extrusion run, and the same reel), some variation is inevitable. This is apparent from the ac breakdown strength measurement, and is the reason that statistical evaluation of the data obtained is a necessity. From what has been noted above, it is likely that these variations are due to inevitable imperfections that result during processing. Figure 6-7 demonstrates the variation in measured ac breakdown strength of crosslinked polyethylene insulated cable. Sample lengths tested were from the same production run and from the same reel. Variations such as these are common and are the reason for employing statistical analysis of data, such as Weibull distribution.

The data shown from the EPRI project was obtained at a five minute step rise time. If the time interval between the steps is increased (e.g., from 5 to 10 minutes), the apparent ac breakdown strength decreases. If the time interval between steps is increased again, to say 30 minutes, the apparent dielectric

strength is reduced even more. In other words, the apparent dielectric strength that one obtains in performing a test increases as the stress is applied more rapidly. [This is analogous to what happens during a tensile strength test for polyethylene; the apparent tensile strength increases as the stress is applied more rapidly]. Therefore, the meaning of an “ac breakdown strength” value is relevant only if the manner in which the test was performed is known. In comparing ac dielectric strength values for different insulation materials, the test should always be performed in the same manner. This holds true whether one is comparing different grades of the same material (different grades of polyethylene) or different insulation materials (polyethylene versus polypropylene), for example.

The testing of thin films or slabs of insulation materials is performed in the laboratory and the opportunity to control the local environment during testing is present. This should be done and should be reported. Since relatively small specimens are involved (compared to full size cables), a large number are usually tested to overcome the inherent variability in results, as noted above. When working with small samples, the opportunity to control the local environment during testing is greater, and reproducibility may be enhanced. Hence the following variables are to be controlled so that the information obtained represents a true representation of the statistical distribution in homogenities for the material under study.

- specimen thickness
- temperature
- electrode shape and size

The reasons for controlling the thickness have been noted. This is especially of increasing importance as the thickness is reduced. Temperature control is vital, as the dielectric strength is related to the temperature of the specimen at the time breakdown occurs. Clearly, when working with small samples, the opportunity to generate experimental data at controlled uniform temperatures [such as by testing in a controlled environment room, or in an oven] is present.

The electrode shape and size represents a significant parameter for small sample testing. The most common electrodes are Rogowski types, where the electrode is curved and inserted into the polymer slab; this provides a uniform stress gradient and enhances the opportunity for obtaining meaningful information. If the electrode-polymer interface is sharp (instead of rounded) the voltage stress will be enhanced at this location. The failure of the test specimen will be induced at this location. Should that happen, the dielectric strength measured will be related more to the manner in which the test was performed (inducing a high localized stress) rather than related to the properties of the insulation itself.

Needle tests are also performed, where a sharp, but controlled radius of curvature exists at the needle tip, and the latter is inserted into the specimen part way to the ground plane. Voltage stress is applied and the dielectric strength is measured; this approach has been used to determine the influence of additives, designed to increase the breakdown strength, and aid in developing superior insulation materials. A detailed description of typical arrangements of electrodes that may be used for dielectric strength testing of thin films is provided by Mathes in the references.

The frequency of measurement may be readily varied in thin film studies, much more easily than for full size cables. While most testing is performed at 60 hertz, testing has also been performed at frequencies ranging to 1,000 hertz. Again, the rate of rise of the field is vitally important, and can readily be controlled.

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5. SUMMARY

The chemical structure of the polymeric insulation determines the magnitude of the dielectric constant and power factor. These two properties are significant at operating stress and generally considered to be "low." Polyolefins such as polyethylene or crosslinked polyethylene have low dielectric constants and low power factors. Low levels of oxidation, generally resulting from processing the polymer, lead to slight increases in these properties. Higher than normal operating stresses are used to determine the dielectric strength of an insulating material. The manner in which the test is designed and performed can influence the results. Statistical evaluation of the dielectric strength data is required. Failure mechanisms are briefly reviewed and the differences between water and electrical trees are noted.

6. REFERENCES

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